Some consequences of compressional tectonics for extensional models of basin subsidence

Kooi, H.; Cloetingh, S.A.P.L.

published in
Geologische Rundschau (-1999)
1989

document version
Publisher's PDF, also known as Version of record

citation for published version (APA)
Kooi, H., & Cloetingh, S. A. P. L. (1989). Some consequences of compressional tectonics for extensional models of basin subsidence. *Geologische Rundschau (-1999)*, *78*, 183-195.

Sonderdruck

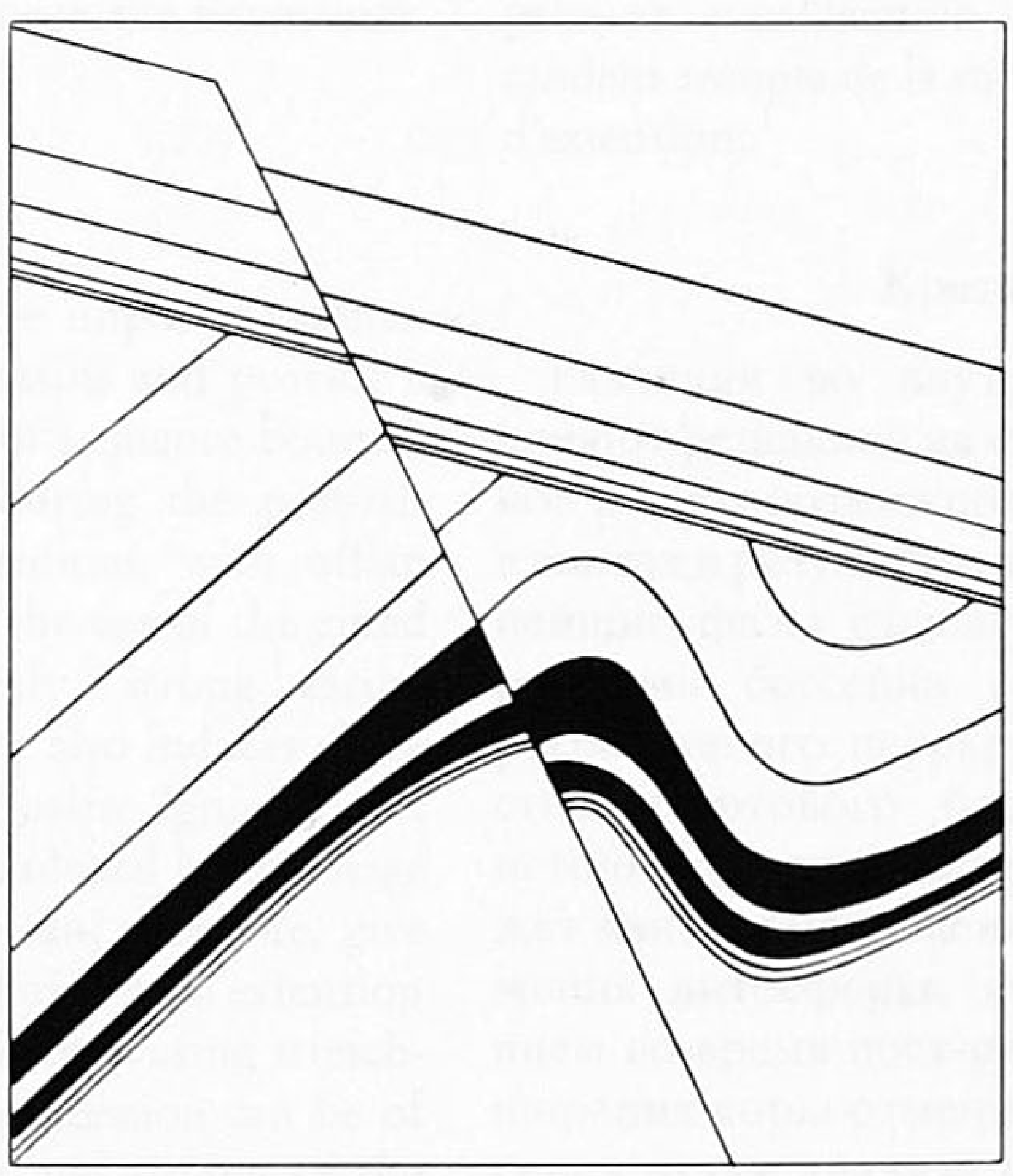
aus

Geologische Rundschau

Band 78, 1989 · Heft 1, Juli 1989

H. Kooi and S. Cloetingh

Some consequences of compressional tectonics for extensional models of basin subsidence



Ferdinand Enke Verlag · Stuttgart

Geologische Rundschau 78/1	183–195	Stuttgart 1989	© Geologische Vereinigung, Mendig

Geologische Rundschau 78/1 | 183–195 | Stuttgart 1989

Some consequences of compressional tectonics for extensional models of basin subsidence

By HENK KOOI and SIERD CLOETINGH, Amsterdam

With 9 figures and 1 table

Zusammenfassung

Unterschiede in plattenintern Streß-Niveaus haben entscheidende Auswirkungen für die Stratigraphie von Rift-Becken und liefern eine tektonische Erklärung für die Erzeugung von Sequenzgrenzen. Späte kompressive Phasen während der post-Rift-Entwicklung von Becken erzeugen Umkonformitäten mit offlap-Phasen, deren Ausmaß mit dem Alter des Rift-Beckens steigt. Entscheidende Fehlerquellen in der Abschätzung der Krustendehnung können darauf basieren, daß die durch späte Kompression während der post-Rift-Entwicklung ausgelösten Vertikalbewegungen der Lithosphäre ignoriert werden. Das Ausmaß der Krustendehnung wird durch Analysen der Basement-Subsidenz mit Hilfe von Dehnungsmodellen entwickelt. Die Quantifizierung der Subsidenz, die von der post-Rift-Kompression gesteuert wird, hat also wichtige Bedeutungen für Extensionsmodelle von Beckensubsidenz.

Abstract

Changes in intraplate stress levels have important consequences for the stratigraphy of rifted basins and provide a tectonic explanation for the generation of sequence boundaries. Late-stage compressional phases during the post-rift evolution of basins produce unconformities, with offlap phases that increase in magnitude with the age of the rifted basin. Late-stage compression has not only a strong bearing on the generation of unconformities, but also induces significant downbending of the centre of a basin. Ignorance of the vertical motions of the lithosphere induced by late-stage compression during post-rift evolution can, therefore, give rise to substantial errors in the estimates of crustal extension derived from analysis of basement subsidence using stretching models. Consequently, late-stage compression can be of great significance in estimates of depth and timing of the hydrocarbon-window inferred from extensional models of basin subsidence. Quantification of the subsidence induced by post-rift compression has important implications for integrated models of basin subsidence and hydrocarbon generation.

Résumé

Les changements dans la distribution des contraintes à l'intérieur des plaques ont des répercussions importantes sur la stratigraphie dans les bassins de rift et fournissent une explication tectonique de la limitation latérale des séries. Des épisodes compressifs tardifs, qui marquent l'évolution post-rift des bassins, sont à l'origine de lacunes dans lesquelles l'importance des phases régressives augmente avec l'âge du bassin. Les mouvements verticaux de la lithosphère induits par ces épisodes tardifs de compression n'étant pas connus, il peut en résulter des erreurs non négligeables dans l'estimation de l'allongement crustal, telle qu'elle est déduite de la valeur de la subsidence du socle dans des modèles d'extension. Dans ces conditions, l'évaluation quantitative de la subsidence produite par les compressions post-rift doit être prise en considération dans l'élaboration des modèles qui rendent compte de la subsidence des bassins par les processus d'extension.

Краткое содержание

Различия во внутриплиточных уровнях стресса влияют решающе на стратографию рифтовых бассейнов и дают возможность объяснить появление границ в свитах в результате тектонических процессов. Позднейшие фазы сдавления во время после-рифтового развития бассейна создают несогласия с фазами регрессивного перекрытия, объем которых с возрастом рифтового бассейна возрастает. Основным источником ошибок при оценке расширения коры может явиться недооценка значения вертикального движения литосферы, вызванное позднейшим сдавлением во время пост-рифтового развития. Объем расширения коры отмечается с помощью модели расширения путем анализа погружения фундамента. Количественная оценка последнего процесса, зависящего от направления сдавления после образования рифта, преобретает т.о. большое значение при построении моделей расширения.

Introduction

Most students of sedimentary basins would agree that intraplate stresses play a crucial role during the formation of basins (e.g., BEAUMONT & TANKARD,

*) Author's address: H. KOOI, S. CLOETINGH, Department of Sedimentary Geology, Free University of Amsterdam, P. O. Box 7161, 1007 MC Amsterdam, The Netherlands.

1987). The formation of rifted basins by lithospheric stretching, for example, requires tensional stresses on the level of a few kbar (Cloetingh & Nieuwland, 1984; Houseman & England, 1986). At the same time, the effect of stress on the subsequent evolution of sedimentary basins has been largely ignored. However, recent work by Cloetingh et al. (1985) and Cloetingh (1986, 1988) has demonstrated that fluctuations in intraplate stress fields have important consequences for basin stratigraphy. Intraplate stresses provide a tectonic explanation for short-term (1–5 Ma) fluctuations in apparent sea level, which finding has great impact on current discussions on the relative contributions of tectonics and eustasy to the stratigraphic record (e.g., Hubbard, 1988; Hallam, 1989; Embry, 1989). Fluctuations in intraplate stress fields modulate (see Fig. 1) the tectonic subsidence induced by the primary driving mechanisms of basin subsidence. These include thermal contraction induced by cooling of the lithosphere amplified by the loading of sediments that accumulate in these basins (Sleep, 1971), isostatic response to crustal attenuation by stretching (McKenzie, 1978), and flexural bending in response to vertical loading (Beaumont, 1978). Post-rift compressive as well as tensional deformations are commonly observed in many basins. For the North Sea Basin, for example, Late Cretaceous and Early Tertiary inversion of parts of subsiding graben systems has been correlated in timing with strong folding phases in the Alpine domain and has been attributed (Ziegler, 1987) to transmission of compressive stresses from the Alpine collision front throughout the Alpine foreland. In previous work (Cloetingh, 1986; Lambeck et al., 1987; Kooi et al., 1989) we have shown that a paleo-stress curve derived from the stratigraphic record of the North Sea area, under the assumption that short-term sea level fluctuations are controlled by the effects of intraplate

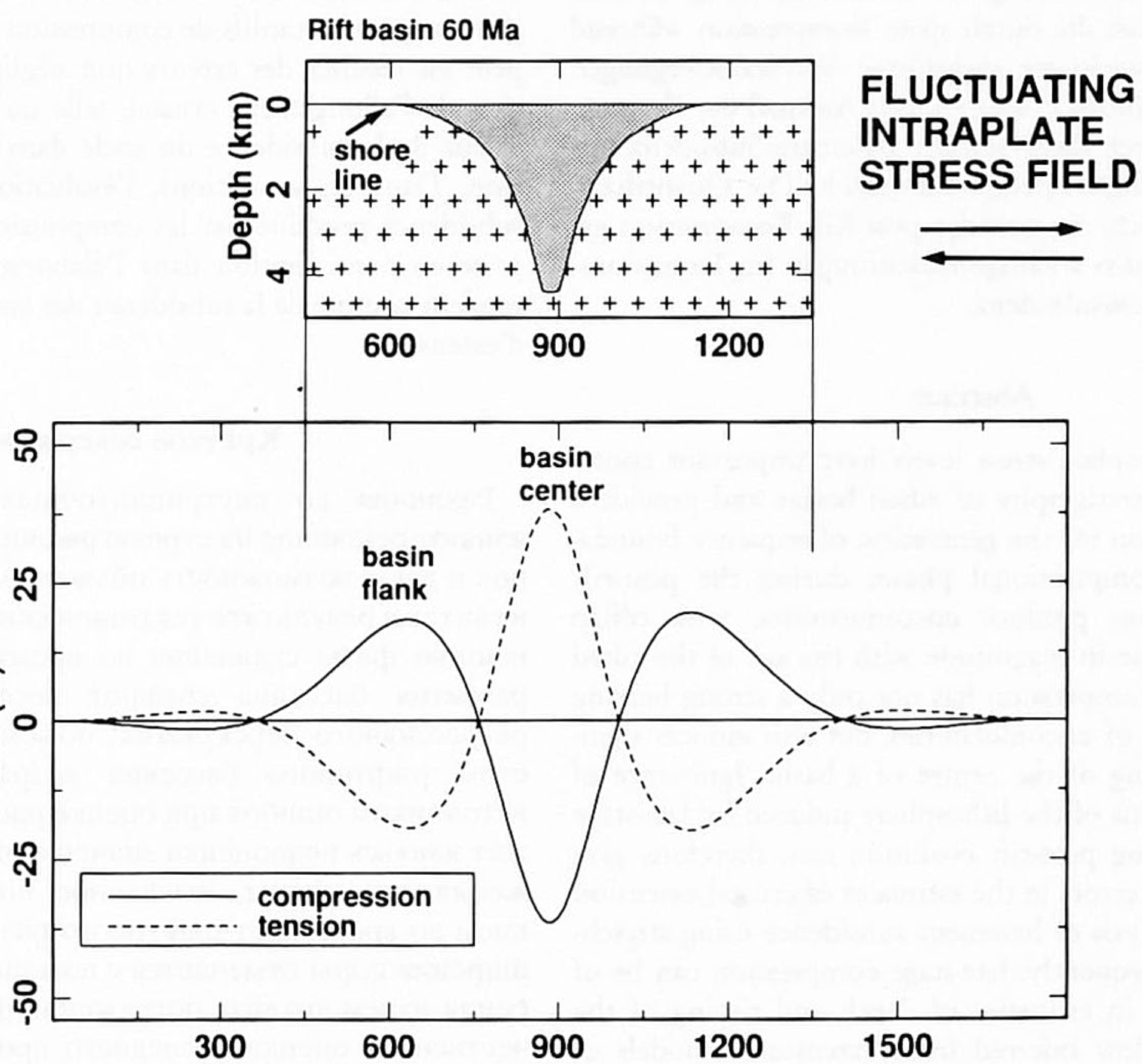


Fig. 1. Flexural deflections at a sedimentary basin induced by changes in the intraplate stress field. Sign convention: uplift is positive, subsidence is negative. Above: a 60 Ma old rifted basin initiated by stretching. The sediments flexurally load an elastic plate. The thickness of this plate varies horizontally due to lateral changes in the temperature structure of the lithosphere. Below: the vertical deflections induced by a change to 1 kbar (= 100 MPa) compression (solid curve). The flank of the margin is uplifted and the basin centre subsides. A change to 1 kbar tension (dashed curve) induces uplift of the basin centre and subsidence of the basin flank. The shape and magnitude of these stress-induced deflections evolve through time not only because of the increasing load, but are also due to changes in the thermal structure of the lithosphere. (After Cloetingh et al., 1985).

stresses, is largely consistent with the documented transition of rift-wrench related tectonics during Mesozoic times to compressional tectonics during Tertiary times in Northwestern Europe (ZIEGLER, 1982; ZIEGLER, pers. comm. 1988).

Substantial progress has been made recently in the study of the lithospheric stress field, due to a concentrated research effort, intensified currently within the framework of the World Stress Map Project (ZOBACK, 1987). Detailed analysis of earthquake focal mechanisms, in-situ stress measurements and analysis of break-out orientation logs taken in wells drilled for commercial purposes have demonstrated the existence of provinces with consistently oriented stress in the lithosphere (ILLIES et al., 1981; ZOBACK et al., 1985; KLEIN & BARR, 1986). The study of paleo-stress fields in the plates by the application of structural analysis techniques (LETOUZEY, 1986; BERGERAT, 1987) has added another dimension to these findings, by demonstrating temporal variations in the observed long-wavelength spatially coherent stress patterns. Numerical modelling (WORTEL & CLOETINGH, 1981; 1983; NEUGEBAUER, 1983; CLOETINGH & WORTEL, 1985, 1986) has yielded better understanding of the causes of the observed variations in stress level and stress directions in the various lithospheric plates. These studies have demonstrated a causal relationship between processes at plate boundaries and deformation in the plate's interiors (e.g., JOHNSON & BALLY, 1986).

In the present paper we present a quantitative analysis of the effect of late-stage compression on the tectonic and stratigraphic evolution of rifted basins. We begin with a brief discussion of the effect of late-stage intraplate compression on basin stratigraphy. Subsequently, we investigate consequences of late-stage compression in failed rift basins for estimates of crustal thinning obtained from current stretching models for basin subsidence. Finally, we discuss implications of this work in the light of evidence from the North Sea and the Gulf de Lions for late-stage compressional tectonics.

Late-stage compression and stratigraphy of rifted basins

Previous studies have demonstrated the important role of thermo-mechanical properties of the lithosphere in models of basin evolution (e.g., WATTS et al. 1982). The increase in flexural rigidity associated with long-term cooling of the lithosphere upon rifting has been shown to explain adequately the long-term widening of rifted basins and the associated long-term (on time scales of several tens of Ma) sea level record. As pointed out by CLOETINGH et al. (1985), changes in stress level in the lithospheric plates induce vertical motions of the lithosphere at basin flanks (or apparent sea level changes) at a rate and magnitude consistent with analysis of the seismic stratigraphic record (VAIL et al., 1977; HAQ et al., 1987). Figs. 2 and 3 schematically illustrate the effects of changes in intraplate stress on the stratigraphy at the edge of a basin calculated for an elastic lithosphere for two different ages of rifted basins (30 Ma and 120 Ma, respectively). The synthetic stratigraphy is calculated using a finite-difference approach (VERWER, 1977) which allows the incorporation of finite and multiple stretching phases and lateral heat conduction (COCHRAN, 1983) into the analysis. When horizontal compression occurs, the peripheral bulge flanking the basin is magnified, resulting in uplift of the basin flanks and seaward migration of the shore line. An offlap develops and an apparent fall in sea level results, possibly exposing the sediments, thus causing the development of an unconformity. Simultaneously, the basin centre undergoes deepening, resulting in a steeper basin slope. For a horizontal tensional intraplate stress field, the flanks of the basin subside. This results in a landward migration of the shore line and an apparent rise in sea level so that renewed deposition with a corresponding facies change in possible. In this case the centre of the basin is shallowed, and reduction of the basin slope occurs.

The synthetic stratigraphy at the basin edge for a 30 Ma old rifted basin is schematically shown for the following three situations: long-term widening of the basin with cooling in the absence of an intraplate stress field (Fig. 2a), the same case with a superimposed transition to $50*10^{12} Nm^{-1}$ in-plane compressional force (equivalent to a 1.2 kbar regional stress field in the 42.2 km thick elastic plate surrounding the basin) (Fig. 2b), and the case of a change to an in-plane force of $5*10^{12} Nm^{-1}$ tension (Fig. 2c). The position of coastal onlap reflects the position where rate of subsidence equals rate of fall in sea level. During application of stress the rate of subsidence is temporally changed. Consequently, the equilibrium point of the coastal onlap is shifted in position. The thermally induced rate of long-term subsidence strongly decreases with the age after rifting (TURCOTTE & AHERN, 1977). Hence as pointed out by THORNE & WATTS (1984), the production of offlaps during later stages of passive margin evolution requires much lower rates of change in sea level than those needed to produce offlaps during the earlier stage of basin evolution. If these offlaps are caused by fluctuations in intraplate stress level, this implies that the rate of change of stress needed to create them diminishes

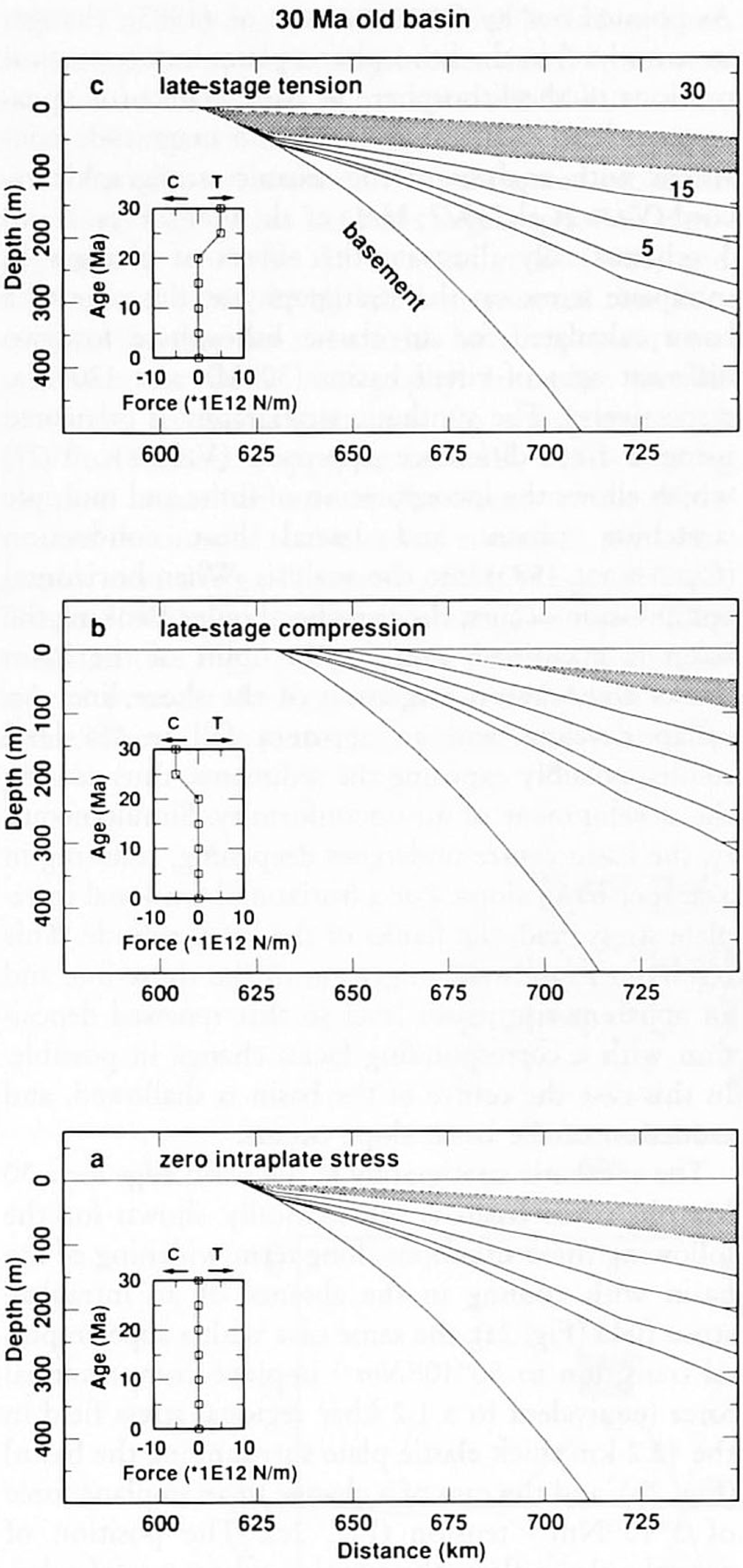


Fig. 2. Synthetic margin stratigraphy for a 30 Ma old rifted basin, which is initiated by lithospheric stretching followed by thermal subsidence and flexural infilling of the resulting isostatic depression. Shading indicates the position of a sedimentary package bounded by isochrons of 20 Ma and 25 Ma after basin formation. a) Stratigraphy with zero-intraplate stresses. b) Effect of a stress change to $5*10^{12}Nm^{-1}$ compressional force (equivalent to a 1.2 kbar regional stress field) from 20–25 Ma. Stress-induced uplift of the peripheral bulge induces narrowing of the basin and a phase of rapid offlap, followed by a long-term phase of gradual onlap due to thermal subsidence. c) Effect of a stress change to $5*10^{12}Nm^{-1}$ tensional force from 20–25 Ma. Stress-induced downwarping of the peripheral bulge causes widening of the basin and a phase of rapid basement onlap.

with age during the flexural post-rift evolution of the basin. This is of particular relevance for an assessment of the relative contributions of tectonics and eustasy as a cause for the development of Cenozoic unconformities at present-day rifted basins. For example, Cenozoic unconformities developed at old passive margins in association with short-term compressional phases of basin narrowing could be produced by relatively mild changes in intraplate stress level. Similarly, given a certain value of stress change, the effect will increase with the ages of the rifted basin involved. This feature is evident from inspection of Figs. 2b and 3b.

Late-stage narrowing is known from a wide range of sedimentary basins and has traditionally been interpreted as either reflecting the response of a rifted basin to a phase of visco-elastic relaxation (SLEEP & SNELL, 1976) or the response to a eustatic sea level fall (WATTS & THORNE, 1984). Hence, the incorporation of intraplate stresses in elastic models of basin evolution provides a simple explanation for late-stage narrowing and resolves a long standing issue which has played a dominant role in arguments between advocates of elastic (e.g., WATTS et al., 1982) and visco-elastic models of basin evolution (e.g., SLEEP & SNELL, 1986). Late-stage narrowing and closure of basins known for example from foreland basin settings, has also been documented for intra-cratonic basins (e.g. North Sea Basin, Michigan Basin and Paris Basin) and passive margins (e.g., U. S. Atlantic Margin). A change to a more compressional stress regime after an early phase of primarily rift/wrench related tectonics adequately explains the late-stage narrowing of rifted basins. Similarly, our finding explain why late-stage narrowing of Phanerozoic platform basins and old passive margins is frequently observed (SLEEP & SNELL, 1976), with only mild active tectonism.

Stress-induced vertical motions in failed rift basins

Many aspects of the tectonic evolution of failed rift basins can by their nature be adequately described by models of lithospheric thinning (MCKENZIE, 1978; BARTON & WOOD, 1984; SCLATER & CHRISTIE, 1980; ROYDEN & KEEN, 1980). In general, crustal thinning in these basins, where extension did not proceed enough to form oceanic crust, varies strongly in a direction perpendicular to the rift axis. Consequently, failed rift basins are often characterized by a narrow graben structure, overlain by a wider saucer-shaped post-rift basin that developed in response to thermal subsidence and flexural loading. This strong differential loading makes these basins very sensitive to fluc-

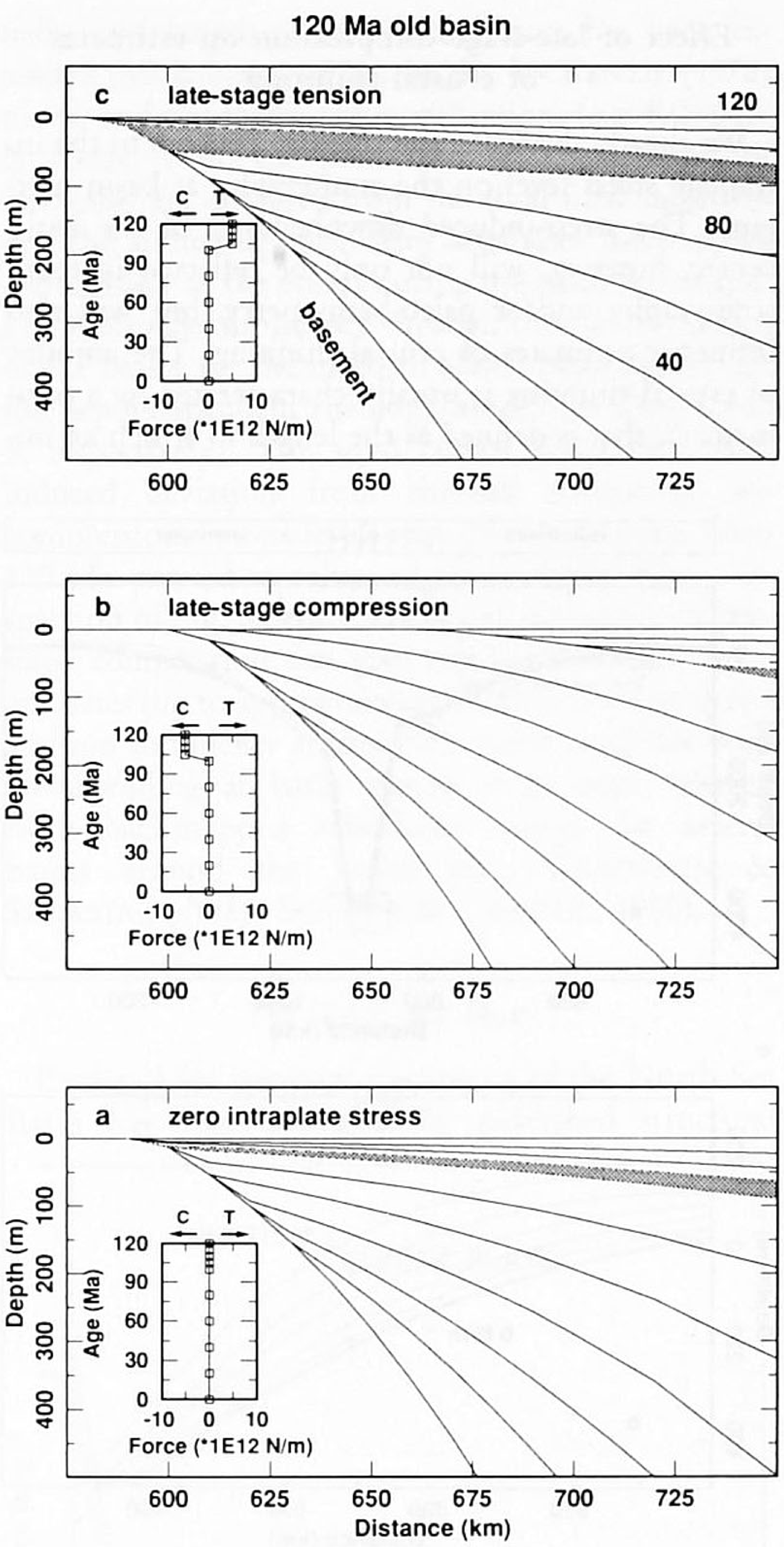


Fig. 3. Synthetic stratigraphy for a 120 Ma old rifted basin. Shading indicates the position of a sedimentary package bounded by isochrons of 100 and 105 Ma after basin formation. a) Stratigraphy with zero-intraplate stresses. b) Effect of a stress change to $5*10^{12}Nm^{-1}$ compressional force (equivalent to a 1.2 kbar regional stress field) from 100–105 Ma. Note the increase in effectiveness of this stress change in producing rapid offlap relative to a 30 Ma old basin (Fig. 2b). c) Effect of a stress change to $5*10^{12}Nm^{-1}$ tensional force from 100–105 Ma.

tuations in intraplate stress level (KOOI et al., 1989). Therefore, failed rift basins provide excellent sites to investigate the implications of late-stage compression for extensional models of basin subsidence.

Fig. 4a shows the basement configuration of a rifted basin for an elastic plate model with varying compressive intraplate stress levels. The deflection of the basin is due to crustal thinning, thermal contraction and flexural compensation for sediment loading. For this model we have adopted an effective elastic thickness, which corresponds to the depth of the 400 °C isotherm.

Evident in Fig. 4a is the widening of the basin due to the lateral strength of the lithosphere which induces downwarping of the basin flanks (located on unstretched lithosphere). As noted previously, increas-

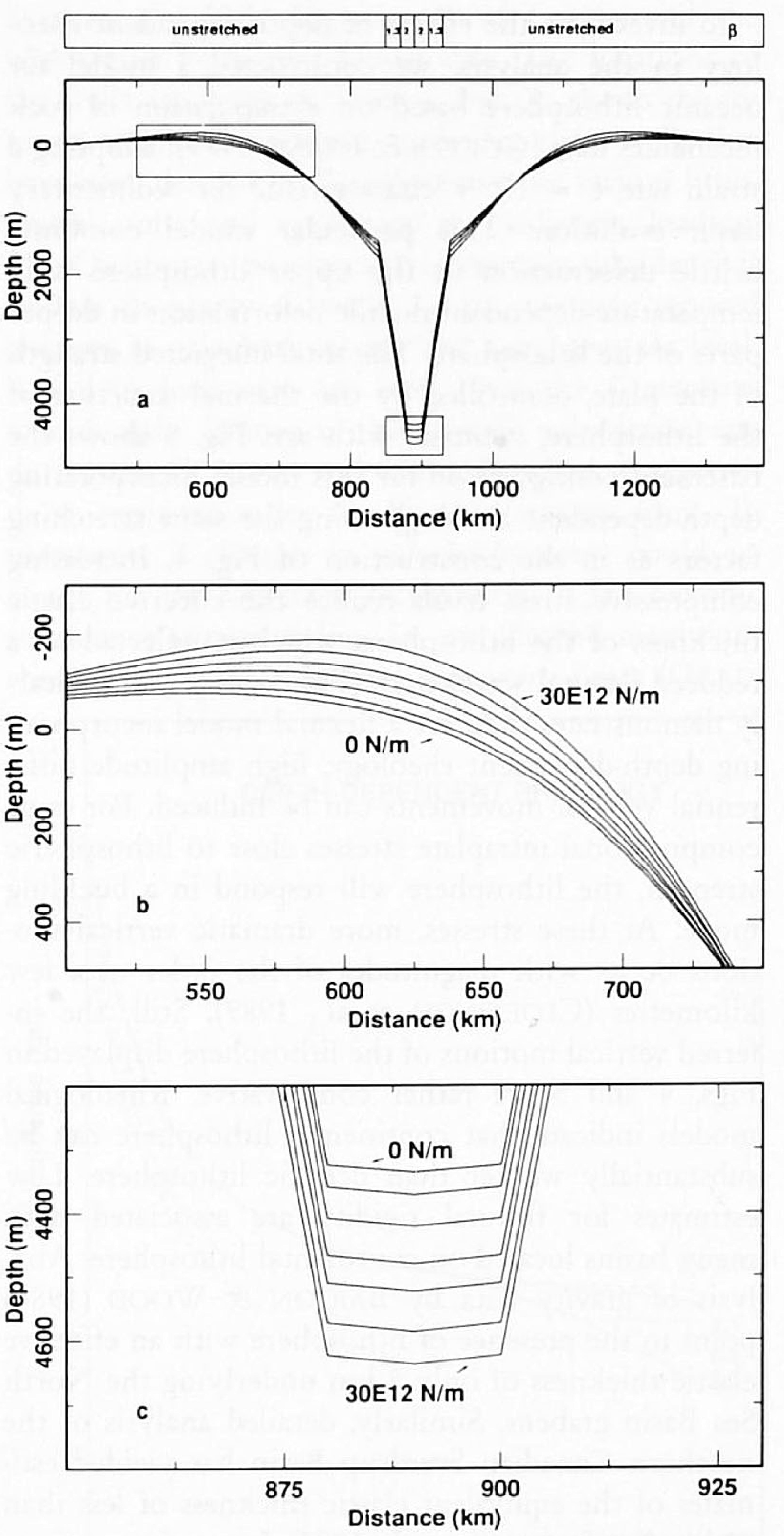


Fig. 4a) Deflection of the lithosphere induced by in-plane compression for a rifted basin underlain by elastic lithosphere. Stretching factors are indicated in the upper panel. b, c) Deflections induced by changes to 0, 4, 10, 15, 20, 25 and $30*10^{12}Nm^{-1}$ in-plane compressional forces, respectively, at positions at basin flank and basin centre indicated by insets in Fig. 4a.

ing intraplate compressional stress levels modify the shape of the basin by inducing gradual uplift of the basin flank, resulting in narrowing of the basin (Fig. 4b), contemporaneous with downbending of the basin centre (Fig. 4c). A more realistic flexural model, incorporating depth-dependent rheology with finite strength, considerably reduces the level of intraplate stress required to produce the amplitudes of the observed differential vertical movements (CLOETINGH et al., 1989).

To investigate the effects of depth-dependent rheology in the analysis, we constructed a model for oceanic lithosphere based on extrapolation of rock mechanics data (GOETZE & EVANS, 1979), adopting a strain rate $\dot{\epsilon} = 10^{-18}s^{-1}$characteristic for sedimentary basin evolution. This particular model combines brittle deformation in the upper lithosphere with temperature-dependent ductile deformation in deeper parts of the lithosphere. The total integrated strength of the plate, controlled by the thermal structure of the lithosphere, increases with age. Fig. 5 shows the basement configuration for this model incorporating depth-dependent rheology using the same stretching factors as in the construction of Fig. 4. Increasing compressive stress levels reduce the effective elastic thickness of the lithosphere, which is reflected by a reduced flexural wavelength (Fig. 5). Fig. 5 also clearly demonstrates that, for a flexural model incorporating depth-dependent rheology, high amplitude differential vertical movements can be induced. For large compressional intraplate stresses close to lithospheric strength, the lithosphere will respond in a buckling mode. At these stresses, more dramatic vertical motions occur with magnitudes of the order of a few kilometres (CLOETINGH et al., 1989). Still, the inferred vertical motions of the lithosphere displayed in Figs. 4 and 5 are rather conservative. Rheological models indicate that continental lithosphere can be substantially weaker than oceanic lithosphere. Low estimates for flexural rigidity are associated with many basins located on continental lithosphere. Analysis of gravity data by BARTON & WOOD (1984) point to the presence of lithosphere with an effective elastic thickness of only 5 km underlying the North Sea Basin grabens. Similarly, detailed analysis of the northern Canadian Sverdrup Basin has yielded estimates of the equivalent elastic thickness of less than 30 km (STEPHENSON et al., 1987). In contrast, estimates of equivalent elastic thickness of old oceanic lithosphere are characteristically of the order of 40–50 km (MCADOO et al., 1985). We, therefore expect that a specific change in intraplate stress will induce larger vertical motions in continental lithosphere than in oceanic lithosphere.

Effect of late-stage compression on estimates of crustal thinning

We already discussed the effect of changes in the intraplate stress level on the stratigraphy at basin margins. The stress-induced downbending of the basin centre, however, will not only be reflected in basin stratigraphy and/or paleo-bathymetry, but will also influence estimates of crustal thinning. The amount of crustal thinning is usually characterized by a parameter β, that is defined as the length to which an ini-

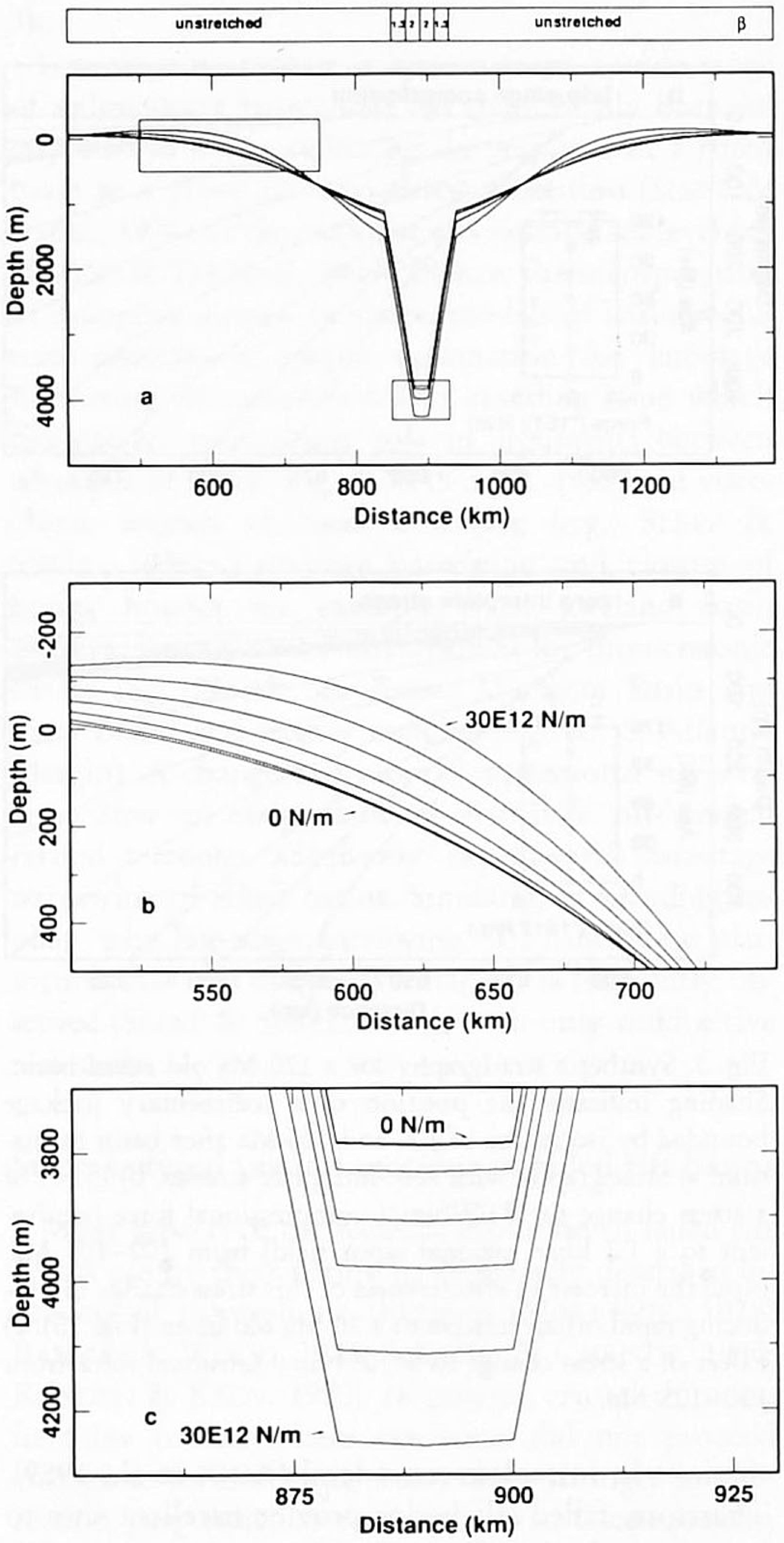


Fig. 5. Basin deflection induced by in-plane compression calculated for a depth-dependent oceanic rheology of the lithosphere based on experimental rock mechanics data (GOETZE & EVANS, 1979), adopting a strain rate of $10^{-18}\ s^{-1}$. Figure convention as in Fig. 4.

tially unit length of continental crust has been extended (McKenzie, 1978). In the McKenzie (1978) model and its subsequent modifications (e.g. Royden & Keen, 1980) the predictions of the amount of extension are obtained from the total final subsidence. The stretching formalism attributes basin subsidence solely to the events during the basin formation. Fig. 6 displays subsidence through time in the centre of the basins for the uniform elastic plate model and the depth-dependent rheology model (see Figs. 4 and 5, respectively). The solid curves show the stress-induced deviation from thermal subsidence for compressional stress levels that linearly increase from 100 Ma onward to values of up to $30*10^{12}Nm^{-1}$. Inspection of Fig. 6 demonstrates that ignorance of late-stage compression can give rise to significant overestimates (up to approximately 15%) in β-values derived from subsidence analysis. Phases of rapid late-stage downbending at basin centres have been inferred from backstripped subsidence curves for several basins around the world (e.g., Gradstein & Srivastava, 1980; Sclater & Christie, 1980).

The North Sea Basin

Evidence for late-stage narrowing of the North Sea Basin has been provided by published structural cross-sections (e. g. Ziegler, 1982). Similarly, deviations from subsidence predicted by thermal models for the North Sea Basin – especially for Plio-Quaternary times (Sclater & Christie, 1980; Kooi et al., 1989) – attest to a tectonic origin for the rapid late-stage subsidence of the basin. To illustrate this we have analyzed the subsidence record of several wells from the Central Graben and the southern Viking Graben of the North Sea using borehole information provided by the Netherlands and Danish Geological Surveys, the U.K. Department of Energy and the Norwegian Petroleum Directorate. The locations of the wells are given in Table 1. Fig. 7a shows the inferred tectonic subsidence curves for these wells that have been derived by decompacting the various lithological units and correcting for sediment loading. Plio-Quaternary acceleration in tectonic subsidence is evident in nearly all wells. So far, we have ignored changes in paleobathymetry and long-term sea level. A fall in long-term sea level since the Cretaceous would only influence the overall subsidence rate during the Cenozoic and could, therefore, not provide an explanation for the Plio-Quaternary event. To investigate if changes in paleobathymetry could account for the late-stage acceleration in the tectonic subsidence curves of Fig. 7a, we adopted maximum shoaling estimates for Plio-Quaternary times (Grad-

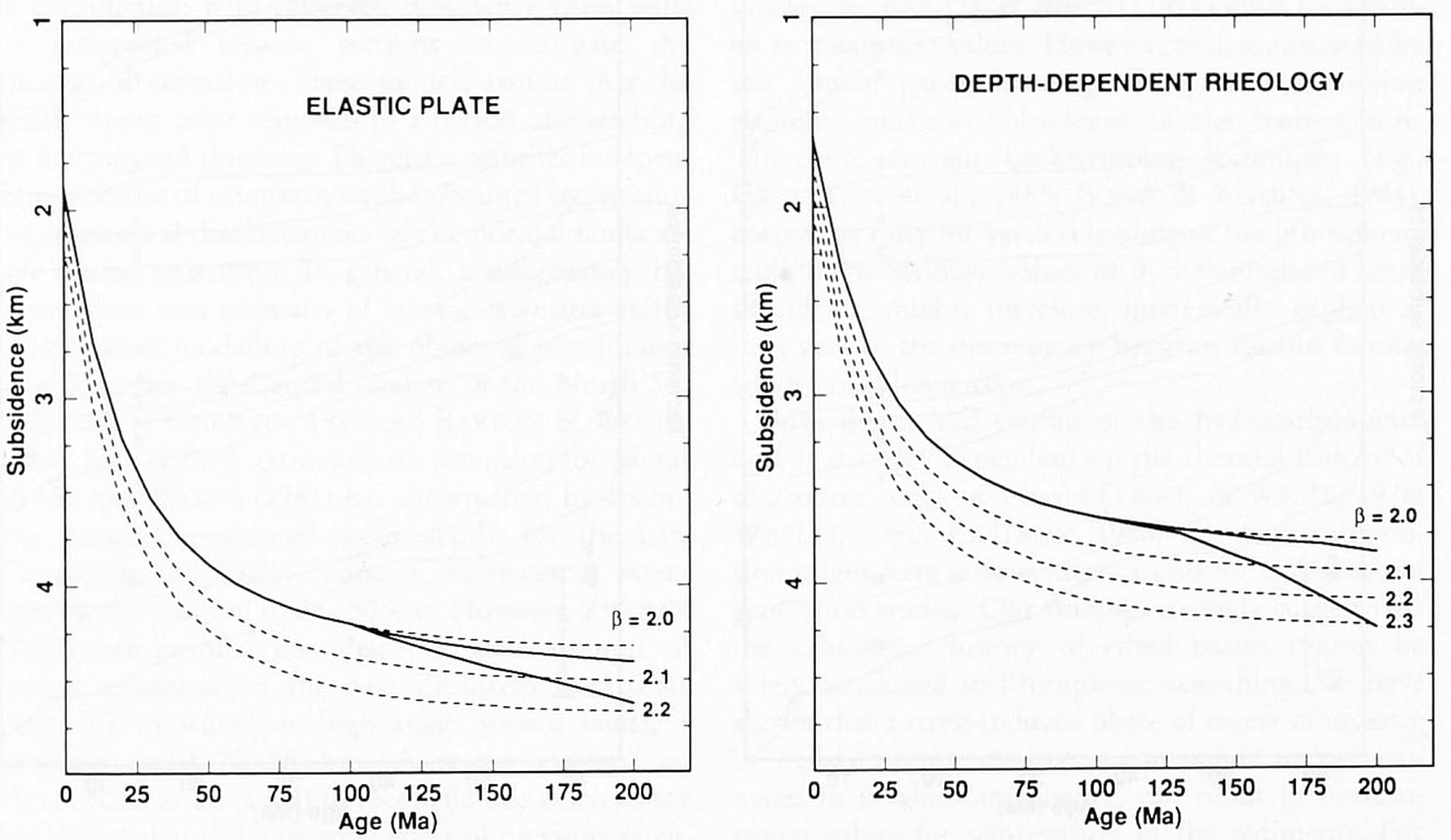


Fig. 6. Left: sediment accumulation through time at the centre of the sedimentary basin shown in Fig. 4. The solid lines indicate sediment accumulation for linearly increasing intraplate compressive stress levels from 100 Ma onward up to 10 and $30*10^{12}Nm^{-1}$ for the upper and lower curve, respectively. Dashed lines denote subsidence in the absence of intraplate stresses for different β-values in the centre of the basin. Right: sediment accumulation through time at the centre of the basin shown in Fig. 5. Solid lines indicate subsidence for the same changes in in-plane stress.

Nr.	Well	Latitude (^0N)		Longitude (^0E)		Sector
1	H-1	55^0	46'	04^0	39'	Danish
2	E-2	55^0	43'	04^0	45'	Danish
3	G17-1	54^0	04'	05^0	31'	Dutch
4	A12-1	55^0	24'	03^0	49'	Dutch
5	F18-1	54^0	06'	04^0	45'	Dutch
6	16/1-1	58^0	59'	02^0	02'	Norwegian
7	25/11-1	59^0	11'	02^0	25'	Norwegian
8	16/7-1	58^0	20'	02^0	19'	Norwegian
9	2/3-3	56^0	48'	03^0	58'	Norwegian
10	15/20-2	58^0	25'	00^0	50'	British
11	30/19-1	56^0	20'	02^0	45'	British

Table 1: Summary of boreholes used in this study.

STEIN pers. comm., 1988). Inspection of the resulting tectonic subsidence curves in Fig. 7b demonstrates that, although changes in paleobathymetry might provide an explanation for the high Plio-Quaternary sedimentation rates in some areas, the majority of the wells are characterized by a net acceleration in tectonic subsidence. Such late-stage accelerations in subsidence are commonly either ignored or attributed to another stretching phase (GREENLEE et al., 1988). We propose that the rapid subsidence phases reflect an increase in the level of intraplate compression in the Northwest European platform. This explanation seems more likely considering the present-day compressional stress field in Northwest Europe (KLEIN & BARR, 1986).

The Gulf de Lions passive margin

Another example of accelerated late-stage subsidence has been documented for the Gulf de Lions passive margin in the Northwestern Mediterranean. This margin has been studied in great detail by the Institut Français du Petrole (BURRUS et al., 1987). This margin was initiated by rifting during Late Oligocene-Early Miocene times (30–23 Ma). The oceanic stage that followed ended around 19 Ma. As noted

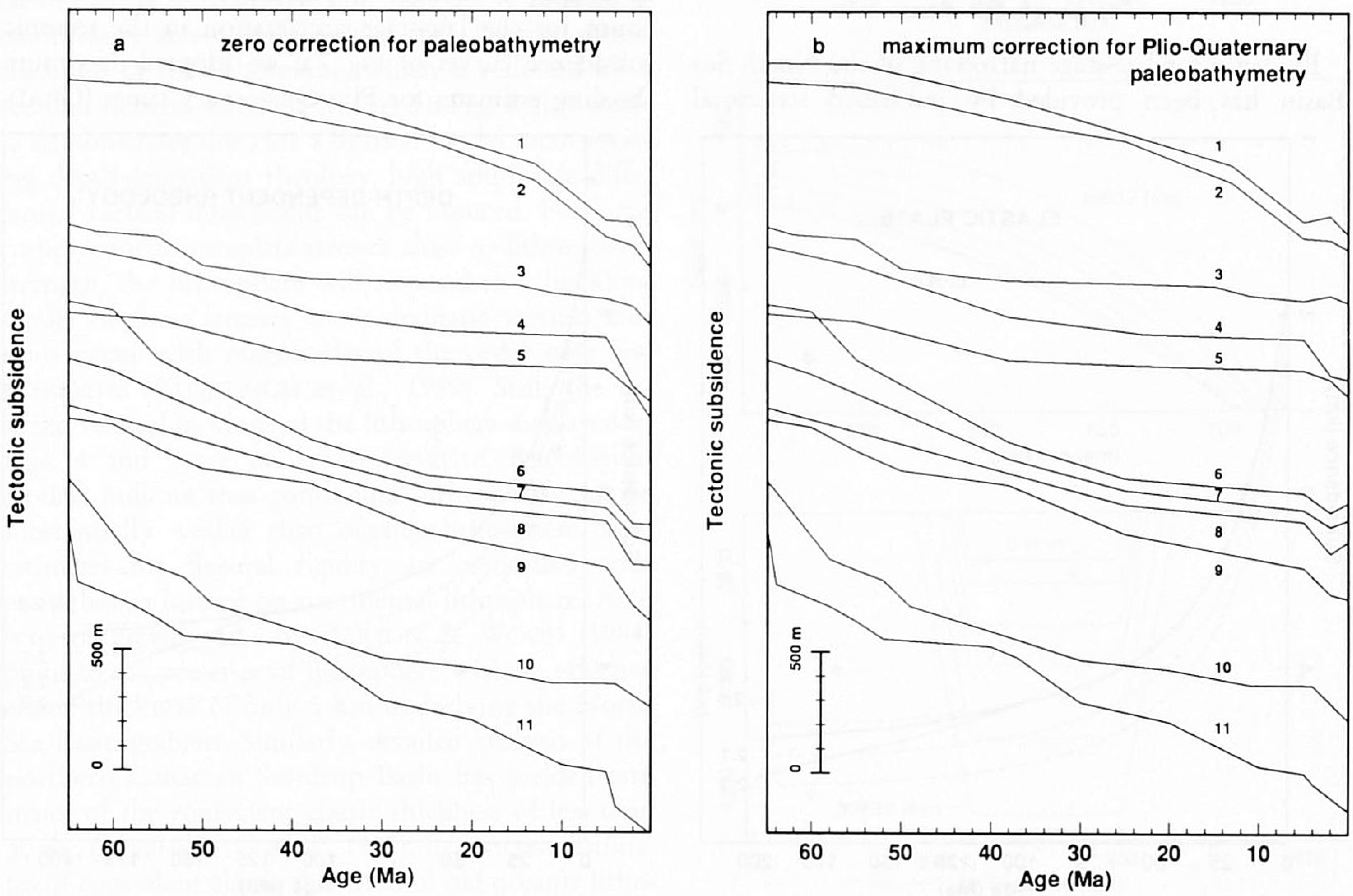


Fig. 7. Tectonic subsidence curves for several wells from the Central Graben and the southern part of the Viking Graben. a) subsidence curves with zero corrections for paleobathymetry. b) subsidence curves with maximum corrections for Plio-Quaternary paleobathymetry. Numbers refer to well locations in Table 1. The figure demonstrates that, although changes in paleobathymetry might provide an explanation for the high Plio-Quaternary sedimentation rates in some areas, the majority of the wells are characterized by a net significant acceleration in tectonic subsidence.

by BURRUS et al. (1987), subsidence curves for various positions along the margin closely follow predictions from thermal models of passive margin subsidence until 7 Ma, but strongly deviate in the last seven Ma of the evolution of the basin (see Fig. 8). Rapid excess subsidence of the order of 500 metres is initiated at the basin centre, while uplift of the order of a few hundred metres is induced at the inner shelf. The rapid vertical differential motions of the basin at 7–5 Ma coincide with a well-documented regional compressive phase (BURRUS et al., 1987). Recently, CLOETINGH et al. (1989) have modelled the overall Gulf de Lions stratigraphy. The predicted subsidence along different positions across the margin was found to be in good agreement with the observed differential basement motions. The stress-induced subsidence and uplift explains the observed record of vertical motions in the Gulf de Lions and explains the deviation of the observed subsidence from predictions of thermal models of basin subsidence.

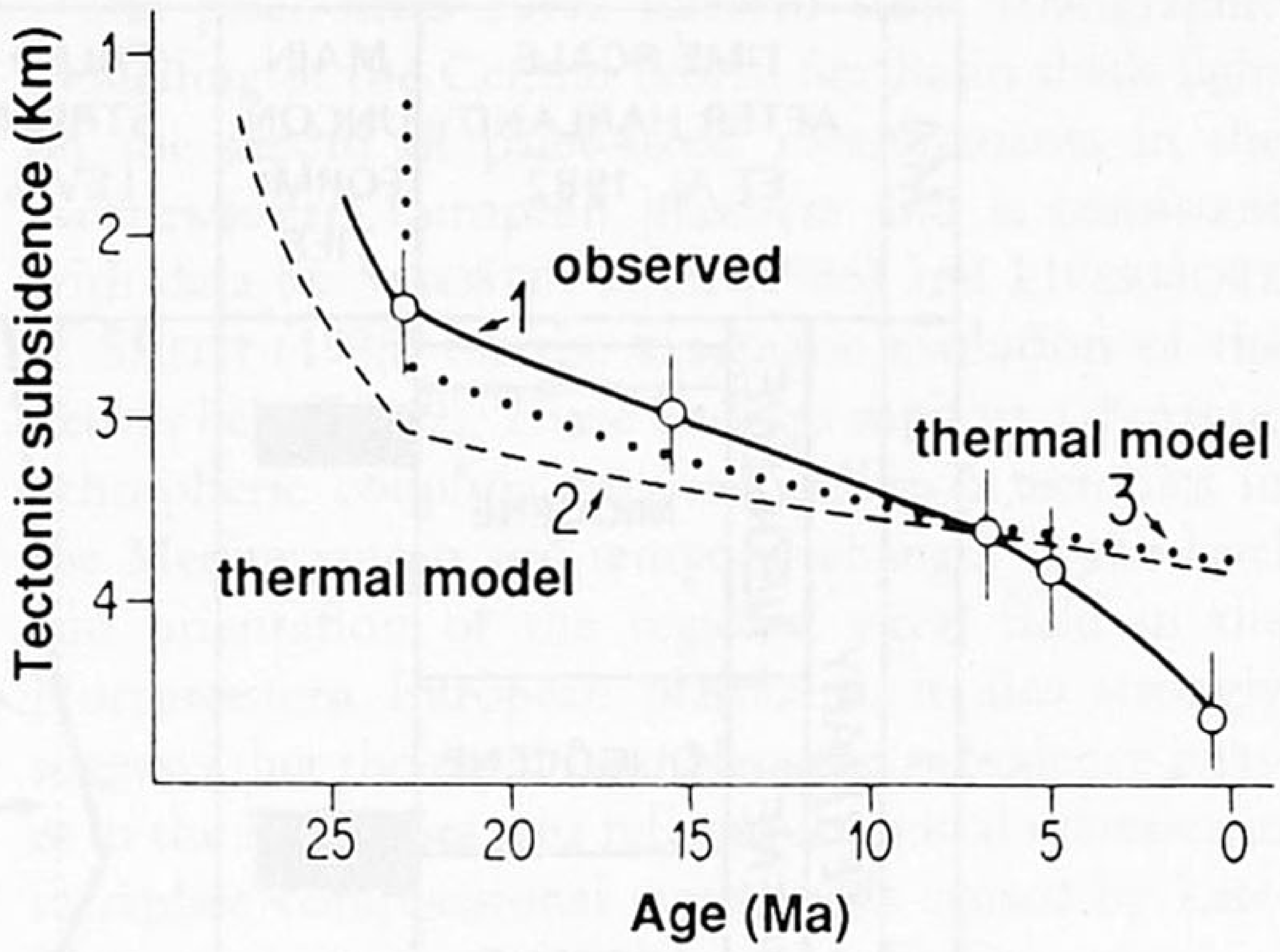


Fig. 8. Observed and calculated tectonic subsidence at the basin centre of the GULF DE LIONS passive margin. Curve 1 (solid curve connecting the data points): reconstructed tectonic subsidence (observed), assuming local isostasy. Curves 2 and 3 (dashed and dotted, resp.): calculated tectonic subsidence from thermal models. Note the rapid excess subsidence since 7 Ma. (After BURRUS et al., 1987).

Implications for stretching models

Simple stretching models (MCKENZIE, 1978; ROYDEN & KEEN, 1980) predict the subsidence history of a basin formed by extension, which can be used in conjunction with observed subsidence from wells or interpreted seismic sections to estimate the amount of extension. These models assume that the brittle upper crust responds to a period of stretching by faulting and thinning. Therefore, another independent estimate of extension can be obtained by measuring horizontal displacements of the normal faults active during extension. In general, a discrepancy between these two estimates of crustal extension exists. Quantitative modelling of the observed post-Jurassic subsidence for the Central Graben of the North Sea (SCLATER & CHRISTIE, 1980 and BARTON & WOOD, 1984) has yielded estimates of extension of about 50–80 km. WOOD (1981) has shown that, by assuming greater depositional water depths for the Late Cretaceous and Early Cenozoic, estimates of extension can be reduced to 25–50 km. However, ZIEGLER (1982) has pointed out that the total amount of crustal extension on the base Zechstein level (Late Permian), measured on high angle normal faults, is probably only 20–25 km. A recent attempt by HELLINGER et al. (1989) to reconcile this discrepancy has shown that if the thermal effect of previous extension phases is taken into account, the estimates of extension from fault analysis lie closer to the range of values inferred from subsidence analysis. Therefore, the estimates of extension of the North Sea Central Graben by BARTON & WOOD (1984) must be regarded as maximum values. However, as demonstrated by the present paper, late-stage intraplate compression strongly enhances subsidence in the basin centre. Therefore, current backstripping techniques (e.g., GRADSTEIN et al., 1985; BOND & KOMINZ, 1984), correcting only for vertical loading of the lithosphere, tend to overestimate values of β. Stress-induced basin subsidence might, therefore, intrinsically explain at least part of the discrepancy between various estimates of crustal extension.

Since depth and timing of the hydrocarbon-window is strongly dependent on the thermal history of the source rocks in a basin (TISSOT & WELTE, 1978; WAPLES, 1980; ESPITALIE, 1986) late-stage compression might have serious implications for hydrocarbon generation studies. Our findings strongly suggest that the subsidence history of rifted basins cannot be solely attributed to lithospheric stretching. We have shown that a stress-induced phase of excess subsidence in the basin centre can give rise to significant overestimates in β-values and, hence, can result in overestimated values for temperature in the sediments. For example, overestimates of 15% in β-values (see Fig. 6) correspond roughly to temperature perturbations of several tens of degrees (MCKENZIE, 1980) at depths corresponding to the hydrocarbon window.

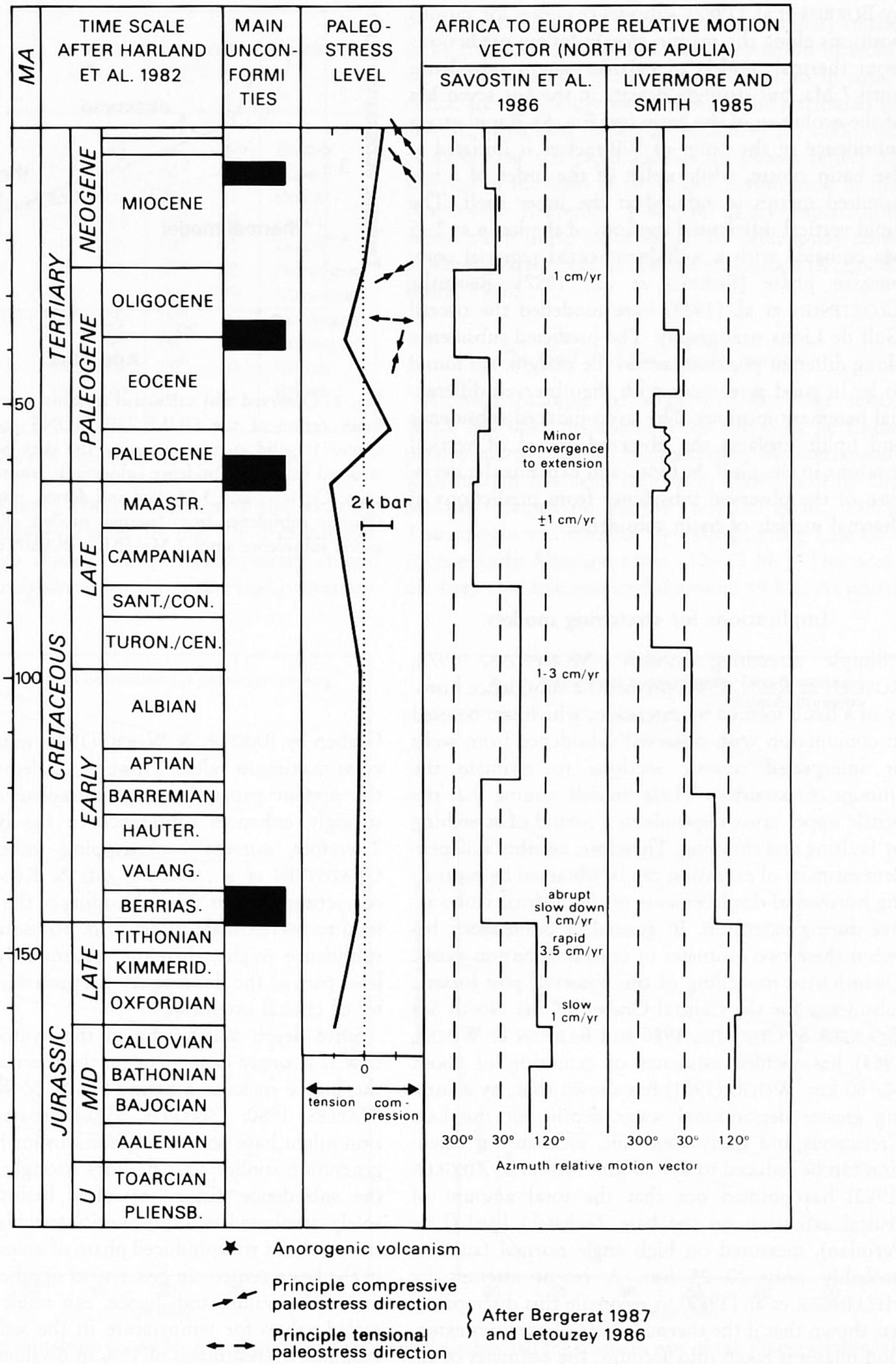


Fig. 9. Synthetic paleo-stress curve as inferred from the forward modelling of the NORTH SEA BASIN stratigraphy. Also shown in this column are paleo-stress orientation data from BERGERAT (1987). The columns on the right show Africa relative to Europe plate motion data after SAVOSTIN et al. (1986) and LIVERMORE & SMITH (1985). (After KOOI et al., 1989).

Paleo-stress field and dynamic lithospheric coupling of Northwestern Europe with Mediterranean collision tectonics

The previous paragraphs demonstrated that the Late-Neogene subsidence history of the Gulf de Lions passive margin and the North Sea basin might be due to a phase of late-stage compression. In general, the passive margins of the Mediterranean, located in a highly active tectonic setting, are to a large extent dominated by compression associated with the Africa-Europe collision. These margins, like the example of the Gulf de Lions given above, therefore offer the prospect to study the near-field effect of intraplate stresses induced by plate-tectonics forces, associated with ongoing collision, on basin stratigraphy and basin subsidence. Basins located at larger distances from plate margins, like the North Sea basin, are the recorders of a far-field, more subtle interplay between intraplate stresses and basin stratigraphy.

Fig. 9 shows the paleo-stress curve resulting from modelling of the stratigraphy of the North Sea Central Graben (KOOI et al., 1989). The trend of the curve with a change from overall tension and neutral stresses during Mesozoic times to a stress regime of more overall compressional character is consistent with the documented change (ZIEGLER, 1982) from a Mesozoic regime of rift/wrench tectonics, associated with the terminal stages of the breakup of Pangea, to a tectonic regime dominated by Alpine collision phases. Superimposed on this long-term trend are stress fluctuations of a shorter period. The paleo-stress curve displays a strong phase of compression during Paleocene/Eocene times corresponding in timing with the occurrence of strong folding phases in the Alpine domain. For Late Eocene to Early Oligocene we predict a stress regime of more tensional character, concomitant with the timing of initiation of rifting in the European Platform, and an associated measured tensional paleo-stress field (LETOUZEY, 1986; BERGERAT, 1987). The predicted overall increase in the level of the post-Early-Oligocene compression is consistent with the observed (LETOUZEY, 1986; BERGERAT, 1987) rotation of the paleo-stress field in Northwestern Europe from NE–SW oriented Late Oligocene/Early Miocene compression to the present NW–SE orientation of the largest compressive stress, a direction which is more perpendicular to the strike of the Central Graben basins (KLEIN & BARR, 1986, see also Fig. 9).

The paleo-stress curve inferred from stratigraphic modelling of the Central North Sea Basin sheds light on the record of paleo-stress measurements in the Northwestern European platform and is consistent with data by SAVOSTIN et al. (1986) and LIVERMORE & SMITH (1985) on the kinematic evolution of the Tethys belt (Fig. 9). These findings support a dynamic lithospheric coupling between collision tectonics in the Mediterranean and temporal changes in the level and orientation of the regional stress field in the Northwestern European plattform. It also strongly suggests that the rapid Late Neogene subsidence phases in the North Sea area reflect substantial increases in intraplate compressional stress levels caused by Late-Neogene tectonic events in the Mediterranean.

Conclusions

The incorporation of intraplate stresses in thermo-mechanical models of basin evolution demonstrates that commonly observed late-stage narrowing of rifted basins is probably associated with a transition to a stress regime of increasing intraplate compression. The effectivity of the compressional intraplate stresses to produce late-stage unconformities increases with the age of the rifted basin. Late-stage compression substantially distorts the record of vertical motions at rifted basins. Ignorance of this effect gives rise to substantial errors in the determination of values of crustal extension inferred from comparison with predictions from thermal models of subsidence of rifted basins. Incorporation of intraplate stresses in basin modelling might contribute to resolve current discrepancies between different estimates of crustal extension. Quantifying the effect of late-stage compressional tectonics has, therefore, important implications for extensional models of basin subsidence and the depth and timing of hydrocarbon generation.

Acknowledgements

Partial support to this work was provided by the Netherlands Organization for Research NWO and by NATO grant 0148/87. Dr. Felix Gradstein kindly provided paleowater-depth data and Gijs Remmelts is thanked for putting borehole data at our disposal. Dr. Peter Ziegler and Dr. Jean Burrus are thanked for helpful discussions and comments.

References

BARTON, P. & WOOD, R. (1984): Tectonic evolution of the North Sea basin: crustal stretching and subsidence. – Geophys. J. R. Astron. Soc., **79**, 987–1022.

BEAUMONT, C. (1978): The evolution of sedimentary basins on a viscoelastic lithosphere: Theory and examples. – Geophys. J. R. Astron. Soc., **55**, 471–498.

– & TANKARD, A. J. (eds.) (1987): Sedimentary basins and basin-forming mechanisms. – Can. Soc. Petrol. Geol. Mem., **12**, 1–527.

BERGERAT, F. (1987): Stress fields in the European platform at the time of Africa-Eurasia collision. – Tectonics, **6**, 99–132.

BOND, G. C. & KOMINZ, M. A. (1984): Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implication for subsidence mechanisms, age of breakup, and crustal thinning. – Geol. Soc. Am. Bull., **95**, 155–173.

BURRUS, J., BESSIS, F. & DOLIGEZ, B. (1987): Heat flow, subsidence and crustal structure of the Gulf of Lions (NW Mediterranean): A quantitative discussion of the classic passive margin model. In: C. Beaumont & A. J. Tankard (eds.): Sedimentary basins and basin-forming mechanisms. – Can. Soc. Petrol. Geol. Mem., **12**, 1–15.

CLOETINGH, S. (1986): Intraplate stresses: a new tectonic mechanism for fluctuations of relative sea level. – Geology, **14**, 617–620.

– (1988): Intraplate stresses: a new element in basin analysis. – In: K. L. Kleinspehn & C. Paola (eds.): New perspectives in basin analysis – Springer (New York): 205–230.

–, KOOI, H. & GROENEWOUD, W. (1989) in press: Intraplate stress and sedimentary basin evolution. – In: R. A. Price (ed.), Proceedings IUGG Symposium on sedimentary basins, Vancouver, Canada, Am. Geophys. Un. Geodynamics Series.

– MCQUEEN, H. & LAMBECK, K. (1985): On a tectonic mechanism for regional sealevel variations. – Earth Planet. Sci. Lett., **75**, 157–166.

– & NIEUWLAND, F. (1984): On the mechanics of lithospheric stretching and doming: a finite element analysis. – Geol. Mijnbouw, **63**, 315–322.

– & WORTEL, R. (1985): Regional stress field of the Indian plate. – Geophys. Res. Lett., **12**, 77–80.

– & WORTEL, R. (1986): Stress in the Indo-Australian Plate. – In: Johnson, B. & A. W. Bally (eds.): Intraplate deformation: characteristics, processes and causes. – Tectonophysics, **132**, 49–67.

COCHRAN, J. R. (1983): Effects of finite rifting times on the development of sedimentary basins. – Earth Planet. Sci. Lett., **66**, 289–302.

EMBRY, A. F. (1989) in press: A tectonic origin for depositional sequences in extensional basins – implications for basin modelling. – In: T. A. Cross (ed.), Quantitative Dynamic Stratigraphy, Prentice-Hall, New York.

ESPITALIE, J. (1986): Use of Tmax as a maturation index for different types of organic matter. Comparison with vitrinite reflectance. – In: J. Burrus (ed.), Thermal modeling in sedimentary basins – Technip (Paris): 475–496.

GOETZE, C. & EVANS, E. (1979): Stress and temperature in the bending lithosphere as constrained by experimental rock mechanics. – Geophys. J. Roy. Astron. Soc., **59**, 463–478.

GRADSTEIN, F. M. & SRIVASTAVA, S. P. (1980): Aspects of Cenozoic stratigraphy and paleoceanography of the Labrador Sea and Baffin Bay. – Palaeogeography, Palaeoclimatology, Palaeoecology, **30**, 261–295.

–, AGTERBERG, F. P., BROUWER, J. C. & SCHWARZACHER, W. (1985): Quantitative stratigraphy – Unesco & Reidel (Dordrecht): 598 pp.

–, KAMINSKY, M. A. & BERGGREN, W. A., (1988): Cenozoic foraminiferal biostratigraphy of the Central North Sea. – In: F. Roegl & F. M. Gradstein (eds.): Proceedings II Workshops Agglutinated Benthic Foraminifera (Vienna) – Abh. Geol. Bundesanst., **41**, 97–108.

GREENLEE, S. M., SCHROEDER, F. W. & VAIL, P. R. (1988): Seismic stratigraphy and geohistory of Tertiary strata from the continental shelf off New Yersey: Calculation of eustatic fluctuations from stratigraphic data. In: R. E. Sheridan & J. A. Grow (eds.): The Geology of North America, v. I–2, The Atlantic continental margin: U. S. – The Geological Society of America, 399–416 pp.

HALLAM, A. (1989) in press: A reevaluation of Jurassic eustasy in the light of new data and the revised Exxon curve. – Soc. Econ. Paleont. Spec. Pub., **42**.

HAQ, B., HARDENBOL, J. & VAIL, P. R. (1987): Chronology of fluctuating sea level since the Triassic (250 million years to present). – Science, **235**, 1156–1167.

HELLINGER, S. J., SCLATER, J. G. & GILTNER, J., in press (1989): Mid-Jurassic through Mid-Cretaceous extension in the Central Graben of the North Sea: Part 1, estimates from subsidence.

HOUSEMAN, G. & ENGLAND, P. (1986): A dynamical model of lithosphere extension and sedimentary basin formation. – J. Geophys. Res., **91**, 719–729.

HUBBARD, R. J. (1988): Age and significance of sequence boundaries on Jurassic and Early Cretaceous rifted continental margins. – Am. Assoc. Petrol. Geol. Bull., **72**, 49–72.

ILLIES, J. H., BAUMANN, H. & HOFFERS, B. (1981): Stress pattern and strain release in the Alpine foreland. – Tectonophysics, **71**, 157–172.

JOHNSON, B. & BALLY, B. (eds.) (1986): Intraplate deformation: characteristics, processes and causes. – Tectonophysics, **132**, 1–278.

KLEIN, R. J. & BARR, M. V. (1986): Regional state of stress in western Europe. – In: O. Stephensson (ed.): Rock stress and rock stress measurements. – Centek (Lulea, Sweden): 33–44 pp.

KOOI, H., CLOETINGH, S. & REMMELTS, G. (1989): Intraplate stresses and the stratigraphic evolution of the North Sea Central Graben. – Geol. Mijnbouw, **68**, 49–72.

LAMBECK, K., CLOETINGH, S. & MCQUEEN, H. (1987): Intraplate stresses and apparent changes in sealevel: the basins of northwestern Europe. – In: C. Beaumont & A. J. Tankard (eds.): Sedimentary basins and basin-forming mechanisms – Can. Soc. Petrol. Geol. Mem., **12**, 259–268.

LETOUZEY, J. (1986): Cenozoic paleo-stress pattern in the Alpine foreland and structural interpretation in a platform basin. – Tectonophysics, **132**, 215–243.

LIVERMORE, R. A. & SMITH, A. G. (1985): Some boundary conditions for the evolution of the Mediterranean region. – In: D. J. Stanley & F. C. Wezel (eds.): Geological evolution of the Mediterranean Basin Springer (New York): 83–98.

MCADOO, D. C., MARTIN, C. F. & POULOUSE, S. (1985): Seasat observations of flexure: evidence for strong lithosphere. – Tectonophysics, **116**, 209–222.

MCKENZIE, D. P. (1978): Some remarks on the development of sedimentary basins. – Earth Planet. Sci. Lett., **40**, 25–32.

– (1980): The variation of temperature with time and hydrocarbon maturation in sedimentary basins formed by extension. – Earth Planet. Sci. Lett., **55**, 87–98.

NEUGEBAUER, H. J. (1983): Mechanical aspects of continental rifting. – Tectonophysics, **94**, 91–108.

ROYDEN, L. & KEEN, C. E. (1980): Rifting process and thermal evolution of the continental margin of eastern Canada determinded from subsidence curves. – Earth Planet. Sci. Lett., **51**, 343–361.

SAVOSTIN, L. A., SIBUET, J. C., ZONENSHAIN, L. P., LE PICHON, X. & ROULET, M. J. (1986): Kinematic evolution of the Tethys belt from the Atlantic Ocean to the Pamirs since the Triassic. – Tectonophysics, **123**, 1–35.

SCLATER, J. G. & CHRISTIE, P. A. F. (1980): Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the central North Sea basin. – J. Geophys. Res., **85**, 3711–3739.

SLEEP, N. H. (1971): Thermal effects of the formation of Atlantic continental margins by continental break up. – Geophys. J. Roy. Astron. Soc., **24**, 325–335.

– & SNELL, N. S. (1976): Thermal contraction and flexure of mid-continent and Atlantic marginal basins. – Geophys. J. Roy. Astron. Soc., **45**, 125–154.

STEPHENSON, R. A., EMBRY, A. F., NAKIBOGLU, S. M. & HASTAOGLU, M. A. (1987): Rift-initiated Permian-Early Cretaceous subsidence of the Sverdrup Basin. – In: C. Beaumont & A. J. Tankard (eds.): Sedimentary basins and basin-forming mechanisms. – Can. Soc. Petrol. Geol. Mem., **12**, 213–231.

THORNE, J. & WATTS, A. B. (1984): Seismic reflectors and unconformities at passive continental margins. – Nature, **311**, 365–368.

TISSOT, B. P. & WELTE, D. H. (1978): Petroleum formation and occurrence. – Springer Verlag (Berlin) 538 pp.

TURCOTTE, D. L. & AHERN, J. L. (1977): On the thermal and subsidence history of sedimentary basins. – J. Geophys. Res., **82**, 3762–3766.

VAIL, P. R., MITCHUM, P. M. Jr. & THOMPSON, S. III (1977): Global cycles of relative changes of sea level. – Am. Assoc. Petrol. Geol. Mem., **26**, 83–97.

VERWER, J. G. (1977): A class of stabilized three-step Runge-Kutta methods for the numerical integration of parabolic equations. – J. Comp. Appl. Math., **3**, 155–166.

WAPLES, D. W. (1980): Time and temperature in petroleum formation: application of Lopatin's method to petroleum exploration. – Am. Assoc. Petrol. Geol. Bul., **64**, 916–926.

WATTS, A. B., KARNER, G. D. & STECKLER, M. S. (1982): Lithospheric flexure and the evolution of sedimentary basins. – Phil. Trans. Roy. Soc. Lond., Ser. A **305**, 249–281.

– & THORNE, J. (1984): Tectonics, global changes in sea level and their relationship to stratigraphical sequences at the US Atlantic continental margin. – Marine & Petr. Geology, **1**, 319–339.

WOOD, R. J. (1981): The subsidence history of Conoco well 15/30–1, Central North Sea. – Earth Planet. Sci. Lett., **54**, 306–312.

WORTEL, R. & CLOETINGH, S. (1981): On the origin of the Cocos-Nazca spreading center. – Geology, **9**, 425–430.

– & CLOETINGH, S. (1983): A mechanism for fragmentation of oceanic plates. – Am. Assoc. Petr. Geol. Mem., **34**, 793–801.

ZIEGLER, P. A. (1982): Geological atlas of Western Europe. – Shell Internationale Petroleum Maatschappij/Elsevier, Amsterdam – 130 pp.

– (1987): Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine foreland – a geodynamical model. – Tectonophysics, **137**, 389–420.

ZOBACK, M. D., MOOS, D., MASTIN, L. & ANDERSON, R. (1985): Wellbore breakout and in situ-stress. – J. Geophys. Res., **90**, 5523–5530.

ZOBACK, M. L. (1987): Global pattern of tectonic intraplate stress. – IUGG, XIX General Assembly, Vancouver, Canada, Program and Abstracts, **3**, 1116.